

## LCA Methodology

## LCA Comparability and the Waste Index

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## Abstract

There are several problems with the current Life-Cycle Assessment (LCA) methods. One of the most serious problems, in our opinion, is incomparability of results. Several industry representatives have expressed that without comparability and benchmarkability LCA will not survive long in the commercial world. It is therefore paramount that comparability is achieved. Incomparability stems from the usage of different functional units, unit processes and, most notably, different impact categorizations. We propose a new index – the Waste Index (WI) – that does not rely upon any of these techniques, but rather measures an imbalance in Nature and relies upon thermodynamics and chemistry – resulting in comparability.

**Keywords:** Benchmarking; comparability; eco-indicator; eps indicator; global warming potential; impact categorization; Life-Cycle Assessment; waste index

## 1 Introduction

Life-Cycle Assessment (LCA) is a long awaited tool for environmental management. However, according to (AYRES, 1995) and our own research, see e.g. (EMBLEMSVÅG and BRAS, 1998b), most (if not all) of the conventional LCA methods, i.e. LCA methods that are similar to the ISO 14000 LCA methodology, suffer from incomparable units of measurement. Comparability, as explained Rolf Bretz of Ciba (JENSEN, ELKINGTON et al., 1997) is 'indispensable': "If we fail to achieve comparability and benchmarkability in the LCA field, we cannot expect LCA to survive long in the commercial world". Thus, incomparability is a huge problem by itself, which we believe is introduced by the usage of functional units, unit processes and impact categorization, but it also leads to lack of data. The lack of data is, in our opinion, mainly attributable to the complete absence of accounting, see (EMBLEMSVÅG and BRAS, 1998a), but it is further enhanced particularly by the usage of unit processes and impact categorization which make information flow difficult/impossible. Another problem is that the LCA methods are, according to (VIGON, 1997), so 'indecipherable' that practitioners find it almost impossible to both understand the method and implement it. Arguably, this offers flexibility, as various

practitioners can implement it as it pleases, but it totally ruins comparability because two studies of the same system can be significantly different. Finally, the current LCA methods lead to political debate (JENSEN, ELKINGTON et al., 1997) mostly due to the impact categorization and interestingly enough, consensus has not been reached regarding a single list of impact categorization. When not even LCA experts agree upon what categorization to use, it is unlikely to gain significant support from industry and lawmakers.

There is much to discuss regarding these issues (a discussion on energy issues can be found in (EMBLEMSVÅG and BRAS, 1998a)), but here we simply investigate the root of incomparability and how to remedy the problem as it relates to indicator choice. In this paper, we present our solution to incomparability on the indicator level, namely, the Waste Index (WI). We compare WI to a scientific indicator; the Global Warming Potential (GWP). The WI is also compared to the well-known Eco-Indicator and the EPS Indicator. Before closure, we go back to the main issue and explain why the WI yields comparability.

## 2 Eliminating Incomparability – Introducing the Waste Index

The Waste Index (WI) is based on the following basic assumption:

Any substance in a sufficient amount beyond the natural amount of the substance in a control volume (environment) can be considered waste (pollution).

By reversing this basic assumption a more general statement can be established: Whatever the concentration of a substance that exists naturally in Nature is, that is what it is supposed to be. Any disturbance to the natural equilibrium of materials is therefore a measure of environmental impact. This leads to our 'Nature Knows Best' Axiom:

Environmental impact can only be measured relatively by benchmarking Nature.

Waste is, hence, defined as all materials (solid, liquids, or gases – toxic, radioactive, or not) created by a human or industrial activity that exceed the natural amount in a specific geographical area of the environment called 'Control

Volume'. More specifically, the 'Control Volume' is the geographical area that is affected by either the generated waste itself, or by the substances into which the waste is decomposing. In general, waste materials do not exist indefinitely, but decompose or are absorbed into natural substances. However, some persist longer than others. Hence, the amount of disturbance of the natural equilibrium, the length of time it persists, as well as the area it affects, all directly correlate to the seriousness of the impact. These preceding assumptions and 'Nature Knows Best' Axiom form the basis of our Waste Index - a simple mathematical metric that measures environmental impact by benchmarking nature. The general expression for the Waste Index (WI) is

$$WI = \sum_{i=1}^M \frac{V^i}{A_N^i} \cdot \int_0^{T_N^i} d(t^i) dt \quad (1)$$

The Waste Index equation consists of the following elements:

- 1) The degradation function,  $d(t)$ , is a mathematical expression for the rate of degradation of a substance in a control volume. It is based on the following first-order differential equation in (SCOW and HUTSON, 1992):

$$- \frac{dC}{dt} = k \cdot C \quad (2)$$

where  $C$  is the concentration of the substance, whose units can be either  $[\text{kg}/\text{m}^3]$  or  $[\text{g}/\text{l}]$ , and  $k$  is a constant. The degradation function for release  $i$  can in principle be of any shape. By assuming constant release and first-order degradation as in Fig. 1, the WI can be expressed as follows:

$$WI = \sum_{i=1}^M V^i \cdot \frac{R^i}{A_N^i} \cdot \int_0^{T_N^i} (1 - e^{-\frac{(T_N^i - t^i)}{t^i}}) dt \quad (3)$$

In the simplest case the degradation function is a step function as in (EMBLEMSVÄG and BRAS, 1997) resulting in a very conservative WI. However, a more appropriate function, yet simple, is a linear degradation function, which yields:

$$WI = \sum_{i=1}^M V^i \cdot \left( \frac{R^i \cdot T_N^i}{2 \cdot A_N^i} \right) \quad (4)$$

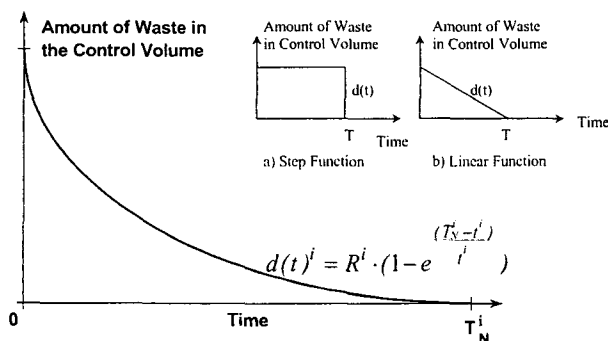


Fig. 1: Degradation of generated waste

- 2) Natural amount  $A_N$  [kg] is the amount that exists naturally of the released substance, or of the substances into which the released substance would decompose, in the specified control volume.
- 3) Released amount  $R(t)$  [kg/h or ton/year] of the released substance, i.e. waste. In cases where the released amount is of no or negligible importance the default value is set to one (1), like for corrosion of iron where the amount of iron is almost irrelevant. For simplicity, we often assess  $R(t)$  on an annual basis and assume it to be constant, denoted as  $R$ .
- 4) Estimated time  $T_N$  [year] the released substance, the waste, will affect the control volume. This is the time it takes Nature to remove the disturbance in the control volume and return to the pre-existing natural balance. In order to use simple degradation formulas, it is assumed that all releases occur as a single release, although more sophisticated release and degradation models can surely be used, if desired. Given this, there are three options for measuring this balance time  $T_N$ , in order of preference:
  1. Direct measurement; the time is measured from the very first emission to the point at which 99.99% of the releases' effects are gone (by convention) – that is, the time the control volume needs to achieve balance again. Direct measurements can be done experimentally in predefined standard environment such as the U.S. Standard Atmosphere, see (COESA, 1976). Although a standard atmosphere is not the same as the real atmosphere, it will give consistent results over time.
  2. Half-times can be used, but then the entire chain of chemical reactions must be investigated and a library of chemical reactions is needed, such as (JACOBSON and HAMPEL, 1946 - 1959). According to (Frank, 1998) such publications are unavailable today, arguably due to the sheer work of making them. However, by using modern information technology, managing such vast amounts of information could be an important role for organizations like ISO, in our opinion.
  3. For toxic substances, biological indicators can be used. For example, in 1989 Tributyltin (TBT), a resistance reducing compound, was banned in coating used on ships smaller than 25 meters (Council Directive 89/677/EEC, 1989). Roughly six years later (EVANS, 1995; WALDOCK, 1995) and (CEFIC, 1996) reported that biological recovery was observed in many coastal dogwhelk and oyster populations. Hence, by using dogwhelk as a biological indicator, similarly to what (THINGSTAD, 1997) did with birds, we can assume that the  $T_N$  is roughly 6 years for TBT.

- 5)  $V$  [-] is the ratio of the control volume affected by a specific waste substance  $i$  ( $V_{waste}^i$ ) [ $\text{m}^3$ ] divided by the control volume for the entire system ( $V_{System}$ ) [ $\text{m}^3$ ], as given in equation (5)

$$V^i = \frac{V_{waste}^i}{V_{System}} \quad (5)$$

Multiple (say  $M$ ) waste substances being released will disperse differently and each will affect a different con-

control volume  $V_{waste}^i$ . Equation 5 represents the normalization of each specific volume affected by the largest possible volume considered, or affected,  $V_{System}$ .

Finally, it is extremely important to use the units consistently so that the WI will be consistent. The unit of the WI is called a Waste Unit (WU). A single Waste Unit is very large; the global release of CO<sub>2</sub> from fossil fuel burning represents roughly 1 WU. We therefore scale it to 1 pico WU = 10<sup>-12</sup> WU = 1 pWU.

From the definition of the WI, we can identify two potential weaknesses:

1. The WI is a simple index with one conceptual problem: The current WI cannot handle biological changes (deforestation, bacteria cultures etc.), because this is a very complicated issue due to reproduction, interplay between various species and so forth. However, for most man-made products this is of little or no concern. Where it is, the issues are often so complex that science often has not provided sufficient hard data for objective decision-making. Nevertheless, we believe that WI represent a significant conceptual improvement compared to the ISO recommended indicators, despite this problem.
2. From a practical point of view we see that there are several variables that must be determined for every chemical compound. This may seem a daunting task, and to some extent it is if all chemicals are to be investigated. However, unlike the ISO recommended indicators, the WI is not related to specific geographical areas and the like because it is based on thermodynamics and chemistry whose laws are the same wherever you are. Also, since the WI does not try to assess the *actual*, or absolute if you like, environmental impact, but rather just the *relative* environmental impact difference between releases, the values for the various chemical compounds only have to be assessed once if researchers would agree (by convention) upon a certain base year with corresponding natural balance to use (we suggest choosing a pre-industrial year), as well as which degradation function to use (we suggest a linear function because it is simple). For the ISO recommended indicators it is not that simple since they try to assess the actual environmental impact which is both geographically and time dependent. Hence, ISO recommended indicators require *much more* information. This is discussed more later in this paper.

Besides the aforementioned problems, lack of data is a problem to some extent, particularly for uncommon materials. This problem will, however, be alleviated as the usage of the WI increases. Another issue is that the WI cannot handle all kinds of environmental problems. This is however an advantage from a comparability perspective since indicators that attempt to capture too much easily becomes incredible. The primary positive aspects of the WI definition are:

- 1) The WI does not have to be normalized according to some chosen functional unit, which would jeopardize the capability of comparison between different products and processes. Instead we normalize releases to Nature itself.

- 2) The WI is continuous and can have any value. This is important because we want the index to handle various materials and chemical compounds under various conditions. The usage of WI for complex systems is shown in (EMBLEMSVÄG and BRAS, 1998b) and thus omitted here.
- 3) The WI is consistent in usage of units and it is comparable from product to product - system to system. This is a major problem for all the LCA techniques known to (AYRES, 1995). In other words, WI is a *relative* index describing how much better/worse a product is to another product, and it is totally apolitical and comparable given a set of axioms and conventions.
- 4) It also meets the four socio-ecological principles of The Natural Step (*Det Naturliga Steget*) organization (founded by the Swedish oncologist Dr. Karl-Henrik Robert in 1989) that must be fulfilled to create a sustainable society (ROBERT, HOLMBERG et al., 1994): (1) *Substances from the lithosphere (earth's crust and mantle) must not systematically accumulate in the ecosphere.* This is taken care of by the waste index as the  $T_N$  will increase as the capability of the ecosystem to handle the releases deteriorates. (2) *Society-produced substances must not systematically accumulate in the ecosphere.* The  $T_N$  will again increase. (3) *The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated.* Again, the  $T_N$  will capture this, because  $T_N$  will be calculated using thermodynamic and chemical models. (4) *The use of resources must be effective and just with respect to meeting human needs.* This will be ensured as the waste drivers can be traced effectively and thereby allowing proper usage of resources. Whether the usage of resources is just or not is a political and ethical issue and cannot be captured by any metric.
- 5) The usage of a system control volume – instead of discrete and subjective scales such as 'local' and 'regional' – facilitates a continuous and unambiguous scaling.
- 6) WI also blends right into an Activity-Based LCA (EMBLEMSVÄG and BRAS, 1997) which is one single method that covers: (1) economic issues, (2) energy issues and (3) waste (pollution) issues. According to the (KEOLEIAN and MENEREY, 1993), these dimensions, and the biological issues mentioned earlier, describe, e.g., a manufacturing process completely. Thus, we have *one* method that can handle *all* numerically measurable and decidable LCA related issues.

Due to the allotted space, significant examples are hard to present in this paper. We refer to (EMBLEMSVÄG and BRAS, 1997 and 1998b) for examples. In this paper, however, comparisons between the WI and the Global Warming Potential (GWP), Eco-Indicator and EPS Indicator are provided, which along with our case studies indicate that the WI is a sound indicator.

### 3 Comparison of the Waste Index and Other Indices

In Table 1, four different types of car fuels are compared using both the WI and GWP. The WI is computed using Equation 4. The NO<sub>x</sub>, CO<sub>2</sub> and CH<sub>4</sub> data in Table 1 are

Table 1: Comparing the waste index and the global warming potential

Type of Car Fuel	NO <sub>x</sub> [g/km]	CO <sub>2</sub> [g/km]	CH <sub>4</sub> [g/km]	Waste Index [WU/km]	GWP [GWP/km]
Petrol Car	0.2600	209	0.0420	2.29E+08	2.91E+02
Diesel Car	0.5700 219.2 %	154 73.7 %	0.0300 71.4 %	3.66E+08 159.7 %	3.29E+02 113.1 %
Methane Car	0.0400 15.4 %	130 62.2 %	0.0720 171.4 %	7.98E+07 34.8 %	1.47E+02 50.6 %
Natural Gas Car	0.0240 9.2 %	83 39.7 %	0.0590 140.5 %	5.03E+07 21.9 %	9.43E+01 32.4 %

Table 2: Input data for calculating the WI and GWP (IPCC, 1993)

Material Name	GWP	Balance Time [years]	Control Volume	Concentration
Carbon Dioxide	1	125.0	Atmosphere	2.80E-04
Methane	68	10.0	Atmosphere	8.00E-07
Nitrous Oxide	303	150.0	Atmosphere	2.88E-07

from David Hart, Centre for Environmental Technology, Imperial College, London and Günter Hörmandinger, Energy Policy Research, London. These data are combined with the data in Table 2, obtained from (IPCC, 1993), yielding the WI and GWP results in Table 1. Note that the large values of WI and GWP are due to the use of concentration instead of actual substance amount in the calculations. However, since the control volume is the same, the relative difference between the values is maintained and a comparison is therefore valid, even though the absolute numerical results are 'wrong' with an unknown, but fixed, correlation factor.

We see that WI and GWP have similar trends and correlate 96%. The WI is, however, assessing diesel fuel to be 60% more harmful than petrol, while GWP does not distinguish much between the two. Since there is no 'objective' benchmark to measure against, we can only conclude that WI and GWP work similarly, with one very significant difference; *the GWP applies only to gasses*. There is also a conceptual difference; GWP is benchmarking releases to a trace gas (CO<sub>2</sub>), while WI is benchmarking a released compound (or what the released compound will decompose into) to the natural amount of that compound in Nature. Hence, the GWP is depending upon the significance of CO<sub>2</sub> w.r.t. global warming, while the WI is not depending upon the significance of any

compound w.r.t. any specific environmental effect. Thus, *the WI can be viewed as a generalization of the GWP*.

Comparing the Eco-Indicator, the EPS Indicator and the WI is more difficult because it is hard to know how the former indices were computed, e.g. what was included, what not, etc. Nevertheless, we used the IDEMAT software by (TU Delft, 1996) as our source of information along with (COESA, 1976; IPCC, 1993) and (MACKAY, SHIU et al., 1992). Furthermore, we could only calculate the WI for atmospheric gasses due to lack of information. In Table 3 the balance times [years] and natural amounts [kg] for the released waste are presented.

The information in Table 3 and  $V^i = 76\%$  entered in Equation 4 yields the information for the various released waste found in Table 4. This information is kept in a separate database for easy access. It is interesting to note that N<sub>2</sub>O has the most severe environmental impact if 1 kg is released, while CO<sub>2</sub> is the least significant. What makes CO<sub>2</sub> so important is the enormous amount of releases. Also note that we have reasons to believe that the SO<sub>2</sub> releases are underestimated in the sense that the whole chain of chemical reactions after acid rain has been formed is not taken into account. For example, acid rain causes releases of heavy metals in soil, which can have devastating long-term effects.

Table 3: Balance times and natural amounts for the waste released

Parameter	CO <sub>2</sub>	CO	NO <sub>x</sub>	N <sub>2</sub> O	SO <sub>2</sub>	Methane	n-Pentane
Balance Time	120	0.21	0.075	150	0.10	10	10.136
Natural Amount	2.11 E+15	3.60 E+11	1.58 E+09	1.48 E+12	6.04 E+10	2.20 E+12	2.20 E+12

Table 4:  $V^i \frac{T_N^i}{2A_N^i}$  for the various waste releases

	CO2	CO	NOx	N2O	SO2	Methane	n-Pentane
$V^i \frac{T_N^i}{2A_N^i}$ [pWU/kg]	0.0215	0.2210	18.0396	38.4597	0.6280	1.7245	1.7479

Table 5: Comparison of WI and the Eco-Indicator and EPS Indicator in production of materials and liquids

Production of Waste Element		Generates Releases of [g]							WI	Eco-Indicator	EPS Indicator
		CO <sub>2</sub>	CO	NO <sub>x</sub>	N <sub>2</sub> O	SO <sub>2</sub>	Methane	n-Pentane	[pWU]	[mPoints]	[mELU]
X10CrNi8 18 9	1 kg			7.80E+00	5.56E-04	1.29E+01	1.54E+00	1.69E-03	0.151127	21.10	4,070
Fe360	1 kg			1.16E+00	9.26E-04	3.39E-01	1.53E+00	1.65E-03	0.023686	4.66	560
CuZn30	1 kg	7.01E+03	4.70E+00	2.73E+01		2.84E+01	8.65E-02	6.47E-02	0.661251	111.00	11,750
E-glass Fiber	1 kg		8.34E-02	3.02E+00		2.28E+00	1.67E-02		0.055913	0.84	145
Glare 1 3/2-0.3	1 kg			1.52E+01	2.50E-03		1.12E+01	2.22E-03	0.293229	31.90	7,378
Hylite 2/1-0.2	1 kg		1.33E-07	1.75E-01	1.74E-01		2.23E+01		0.045156	18.60	1,493
Concrete, Plain	1 kg			1.04E-01	1.22E-04	6.43E-02	3.52E-02	9.89E-05	0.001981	0.66	20
Crude Oil	1 kg	1.80E+02	7.00E-02	2.20E+00		9.00E-02	1.70E+00		0.046466	0.32	442
Diesel	1 kg	2.84E+02	8.00E-02	2.90E+00		1.80E+00	2.90E+00		0.064442	0.62	466
Natural Gas	1 kg	2.09E+00	5.04E-03	2.01E-04			1.32E-03		0.000052	0.47	449
Petrol	1 kg	2.70E+02	8.60E-02	3.07E+00		1.10E+00	3.02E+00		0.066969	0.63	458
Leather	1 kg	2.38E+03	2.47E-01	3.56E+00		1.79E+00	1.21E+02		0.324018	31.70	679
Nitrile Rubber	1 kg			1.08E+01		9.14E+00	1.50E+01		0.226590	3.67	990
HPDE	1 kg	9.40E+02	6.00E-01	1.00E+01		6.00E+00	2.10E+01		0.240231	2.78	768
Cotton	1 kg			1.55E+00	8.15E-01	7.02E-02	1.03E+00		0.046491	5.40	30,329
Polyester	1 kg	1.63E+04	4.59E+01	5.36E+01		7.06E+01	5.67E+01		1.467814	17.20	1 687
Pitch Pine	1 kg				3.20E-03	5.98E-02	9.77E-01	8.23E-03	0.001856	1.14	125

The final WI is achieved by multiplying the ratios for the various waste releases in Table 4 with their respective magnitude found in Table 5. The left columns are the materials that are produced and assessed by the three indicators in the three right columns. In the two right columns in Table 5 the corresponding values for the Eco-Indicator and the EPS-Indicator are shown. All the columns in the middle are the waste releases [g] generated during production of 1kg of the materials.

For example, for Fe360, i.e. construction steel, we take the value of, e.g., NO<sub>x</sub> in Table 4 which is 18.0396 pWU/kg, and multiply it by 1.16g = 0.00116 kg (→ Table 5). This yields a WI for NO<sub>x</sub> of 0.0209 pWU. This calculation is done for each individual waste release (N<sub>2</sub>O, SO<sub>2</sub>, methane and n-pentane) associated with production of 1kg Fe360. Next, all WI results for the individual waste releases are added together, yielding a total WI sum of 0.023686 pWU (→ Table 5). Hence, with the information from IDEMAT

and using the WI, NO<sub>x</sub> releases constitute 88.3% of the environmental impact of producing 1kg of Fe360. The validity of the information provided by IDEMAT is questionable, however. For example, how is it possible to produce, e.g., stainless steel (X10CrNi8 18 9) without emitting CO<sub>2</sub>? This clearly suggests that the analyses presented in IDEMAT are flawed to a certain extent by either excluding emissions or by the fact that parts of the value chain up to the assessment point (production) are missing. From this we understand that the information the comparison is based upon is not 100% reliable. Nevertheless, in Table 6 the results of a simple correlation analysis are presented. We see that the WI correlates about 43.7% to the Eco-Indicator, while it hardly correlates to the EPS indicator. But the EPS Indicator, on the other hand, correlates negatively with methane, which has a GWP of 68. From Table 6 we assert that the EPS indicator handles atmospheric emissions poorly. We can also see that both the Eco-Indicator and the EPS Indicator

Table 6: Correlation matrix for releases and the indices

	CO <sub>2</sub>	CO	NO <sub>x</sub>	N <sub>2</sub> O	SO <sub>2</sub>	Methane	n-Pentane	WI	Eco-Indicator	EPS-Indicator
CO <sub>2</sub>	100.0 %	94.7 %	98.5 %	N/A	99.1 %	30.8 %	N/A	99.5 %	37.5 %	35.3 %
CO		100.0 %	92.3 %	N/A	95.9 %	29.1 %	N/A	93.4 %	8.3 %	8.4 %
NO <sub>x</sub>			100.0 %	-34.8 %	99.0 %	26.6 %	85.5 %	98.0 %	44.3 %	3.6 %
N <sub>2</sub> O				100.0 %	-25.7 %	-4.9 %	84.5 %	-17.3 %	-18.9 %	94.1 %
SO <sub>2</sub>					100.0 %	27.7 %	87.9 %	97.6 %	38.3 %	0.9 %
Methane						100.0 %	-28.9 %	44.1 %	14.2 %	-15.5 %
n-Pentane							100.0 %	88.1 %	94.2 %	77.7 %
WI								100.0 %	43.7 %	3.9 %
Eco-Indicator									100.0 %	29.3 %
EPS-Indicator										100.0 %

correlate only slightly with the atmospheric releases, but more interestingly they hardly correlate between themselves. This suggests that even with the same information, these two indices produce different result. The difference w.r.t. the WI *can* be caused by the lack of information. A full-scale case study can therefore not shed significantly more light upon indicator comparison, except to determine which gives the most acceptable, but maybe not truly correct, results.

So is this just a matter of getting enough information? For the WI it is as explained earlier, but for the two others it is not. The reasons are that for the WI (and GWP) we only need to establish the set of information of a chemical compound once, while for the Eco-Indicator and the EPS indicator we need to find new information whenever the unit processes, the impact categorizations and/or the implementations are different. Consequently the Eco-Indicator, the EPS Indicator and other conventional indices are extremely information intensive and therefore costly. Furthermore, as explained next, the conventional indices inherently produce incomparable results.

#### 4 How the Waste Index Sustains Comparability

In our opinion, incomparability is *not* resulting from lack of data, but rather from the way the ISO LCA method is defined. To show that the WI sustains comparability, we first show what causes incomparability and then compare to the WI.

##### 4.1 The problem of functional units

ISO (ISO/TC 207/SC 5, 1996a) promotes the usage of functional units, defined as 'the functional outputs of the product system whose primary purpose is to provide reference to which the inputs and outputs are normalized'. For example, 'systems A and B perform functions *x* and *y* which are represented by the selected functional unit, but system A performs function *z* which is not represented in the functional unit. As an alternative, systems associated with the delivery of function *z* may be added to the boundary of system B to make the systems more comparable'. Clearly, the usage of functional units does not make comparison easy, and how can 20 products with several important functions each, be dealt with using functional units? On one hand, functional units *can* serve a purpose for industrial products where the customers are interested in products that fulfill a specific function, but on the other hand, finding the functional units can be almost impossible. In (FET, EMBLEMSVÄG et al., 1996), for example, they attempted to find the functional units for a platform supply vessel, its engines and its hull, but the formulation of functional units turned out highly problematic. Furthermore, if nonlinear relations exist between the functional unit and the function, like fuel consumption of a ship and the mass of cargo, then the functional unit is highly misleading as a basis for comparison. Moreover, the usage of functional units totally breaks down for consumer products, because consumer preference can often not be represented by a functional unit, for example, we do not buy a car based on e.g. transportation costs per driver mass. Also, alternative design solutions can often be represented by various function struc-

tures, which by default require different functional units, thus, the result is incomparability. So why even try to normalize the output to something few cares about and nobody can measure well?

The WI, on the other hand, does not use functional units at all, which is evident from the definition of the WI since it is totally independent on the *functional* output of the system. The WI only considers the (annual) releases from a system, geographical area affected, and their (natural) degradation times. Some may argue that this is an implicit functional unit. However, the WI uses the same fundamental properties in all assessments, allowing comparability and avoiding the pitfall of incomparable functional units.

##### 4.2 The problem of unit processes

The usage of unit processes is also promoted in ISO LCA method. A unit process is defined as 'the smallest portion of a product system for which data are collected when performing a life-cycle assessment' (ISO/TC 207/SC 5, 1996b), or 'the basic building blocks within the system boundaries' (JENSEN, ELKINGTON et al., 1997). A major problem arises, however, if a company defines or has unit processes that do not match the unit processes of any known LCA software or database. Then impact assessments are impossible (or they can in the best case be approximated crudely or done manually). This was, for example, the reason for the break down of the assessments in (FET, EMBLEMSVÄG et al., 1996): SimaPro 3.5 simply did not have any unit processes describing the operation of ship machinery, to name one example. Now, taken into account that there are more than eight million chemical compounds and materials in commercial usage today (see the Beilstein and Gmelin databases) out of which 60,000 (National Academy of Sciences, 1984) were toxic substances commonly used in 1984, establishing unit processes seems a rather daunting, if not impossible approach. Furthermore, among toxic substances some are up to 1,000,000 times more toxic than others (HORVATH, HENDRICKSON et al., 1995), hence to not investigate substances used in very little annual amount, i.e. less than e.g. 1 kg, can introduce serious flaws in the analysis. Also, unit process databases will be highly dependent on updates needed due to changes in technology. And economies of scale may cause the differences between similar unit processes. For actual factory environmental management more accurate modeling of processes is required.

The WI is built on thermodynamics and chemistry and does therefore not rely upon specific processes but rather on the fundamental processes in Nature for degrading chemicals and substances. As new chemicals are introduced we only need to study them once, assess their decomposition in terms of control volume/geographical area affected and time, and then publish that information. Creating such publications and associated databases could be a productive role for ISO in our opinion. Thus, the WI is generic and enhances comparability. But clearly, regardless of what approach one chooses, data is needed. The question is which approach is the least information intensive, and we believe the WI is in the long run.

### 4.3 The problem of impact categorization

One major problem with impact categorization is that it leads to political debate (JENSEN, ELKINGTON et al., 1997) as people disagree which emissions affect which impact categories and to what extent. In fact, consensus has not been reached for a single list. Obviously, if monetary taxes were associated with environmental impacts based on particular weighting and categorization schemes, never-ending discussions and political debate and ultimately no action could be the outcome. For example, during the Kyoto meeting in December 1997, the delegates had enormous problems of agreeing upon just the greenhouse effect, which is one out of roughly ten categories, and it did not stop there: According to (MESERVE, 1998); 'the legislative prospects were so bleak that the [US] administration didn't even bother to introduce the Kyoto global warming treaty for ratification'.

Interestingly enough, the categorization that, e.g., Eco-Indicator is built upon, is not the one that ISO recommends according to (JENSEN, ELKINGTON et al., 1997), but the Eco-Indicator is nevertheless one of the most popular indices used today. To further enhance confusion; the ISO list is not the same as the 'Nordic list' see (LINDFORS, CHRISTIANSEN et al., 1995), nor the *two* lists that SETAC have proposed, see (UDO DE HAAS, 1996) and (SETAC-Europe, 1992). Although one could argue that different lists represent different (regional) preferences, it clearly does not facilitate benchmarking. Regardless of category definition, even if that happens to be the same, there are more than enough crossroads where practitioners can go wrong:

1. During classification, the next step in impact categorization, double, triple etc. counting is needed since various emissions can affect several categories. This requires that the practitioners have very good understanding in the effects of every emission, or access to a database that provides this information.
2. An implicit assumption in classification is 'less is better' (ISO, 1997), which in cases where compromises between various emissions must be made can lead to wrongful decisions as less is not always better. For example, Heiner Geiss at the Forschungszentrum Jülich challenges conventional belief by claiming that the catalytic converters in cars *increase* the formation of ground-level ozone due to the changed ratio between  $\text{NO}_x$  and VOC in the air despite the initial reduction of NO emissions (SEEHUSEN, 1998). Kjetil Tørseth at Norsk Institutt for Luftforskning (NILU) totally rejects this claim.
3. The next step in impact categorization is characterization, where one tries to assign the relative contribution of the relevant environmental processes (JENSEN, ELKINGTON et al., 1997). This is based on scientific knowledge, however when that is not available one simply makes value-choices. The result is that one mixes apples and oranges resulting in incomparability.
4. The last step is the weighting or valuation. The purpose is to rank, weight and possibly aggregate the results to arrive at the relative importance of the results (ISO, 1997). Since stakeholders are allowed to impact the weighting scheme the end result is nothing but doubtful

and over time completely incomparable. Methods for weighting are presented in (LINDEIJER, 1996).

5. Throughout impact categorization, one also tries to establish a geographical area of impact. This is done using scales such as 'Global', 'Continental', 'Regional' and 'Local'. We think that these scales are ambiguous, subjective and incomparable. Global and continental are fairly accurate, although incomparable. The WI, in contrast, uses control volumes that are both continuous and unambiguous in the sense that they are measured in quantitative units.

From this we understand that the probability of having comparable studies using the ISO approach and other conventional approaches is very low. An illustrative case study of these problems, and more, is given in (EMBLEMSVÄG and BRAS, 1998b).

The WI attempts to avoid the above pitfalls by simply benchmarking Nature. The geographical impact area is handled by control volumes which are measured clearly. The result is a purely relative, yet *reliable and comparable*, measurement that allows us to get a valid *comparison* of environmental impact for widely different systems, but it does *not* say how much a specific release contributes to specific environmental effects. Although choices are also made for the WI, all such choices are made once and for all and upfront. Hence, the WI avoids continuous value-choice-decision-making that is virtually a necessity for the conventional LCAs and that causes serious incomparability.

### 5 Biological Diversity Degradation and Human Health Risks Issues

Clearly, the WI is only concerned with the general state of the environment. The problems of biological diversity degradation and human health risks are therefore not considered

. Obviously, it is important to handle the biological diversity, because preserving the biological diversity is important for humans both directly and indirectly via the usage of biological entities. Many natural systems sustain cycles of disturbance (fire, hurricanes, disease) and rejuvenation (RICKLEFS, 1990) and rely on re-colonization. But as habitats become more and more fragmented (e.g., forests by the spread of agriculture and urban development) disturbances can so thoroughly destroy an area that little chances are left for complete recovery, even with substantial help from humans (JANZEN, 1988). Furthermore, any reduction in biological diversity can upset the balance of a system and alter its function (WILSON, 1988). Thus, it seems that preserving a high biological diversity is just as important in the long run as any other measurement of the state of our environment. In fact (LOVELOCK, 1988) proposes a theory - the Gaia Theory - where living systems (biological entities) and nonliving systems co-evolve and in fact *produce* the environment. It is also important to handle *human* health risks because humans are large mammals that can be extinct even though the general state of the environment has changed relatively little.

In principle, we can include these issues in the definition of our Waste Index by using penalty functions that will come

into play when released wastes exceed certain threshold limits and thereby increasing the WI. However, after some initial investigation, we believe that such an approach is not likely to work at this moment, because we only have *partial* assessments and data for 5% (National Academy of Sciences, 1996) of the chemicals in the environment. Some data for exposure limits for humans can be found in (American Conference of Governmental Industrial Hygienists, 1996). Thus, an attempt to incorporate biological diversity and human health risk issues into the WI is currently not realistic, in our opinion. We believe that currently these two issues should be handled by simply using separate indicators. Those indicators serve as 'flashlights' alerting a practitioner when releases have negative effects related to human health and/or biological degradation. The following expressions can be useful for the biological diversity and human health risk indices for a released waste  $i$ , respectively:

$$I_{BD}^i = \begin{cases} 1 & \text{if } \frac{R^i}{V_{BD}^i} \geq C_{BD}^i \\ 0 & \text{if } \frac{R^i}{V_{BD}^i} < C_{BD}^i \end{cases} \quad (6)$$

$$I_{HH}^i = \begin{cases} 1 & \text{if } \frac{R^i}{V_{HH}^i} \geq C_{HH}^i \\ 0 & \text{if } \frac{R^i}{V_{HH}^i} < C_{HH}^i \end{cases} \quad (7)$$

Where:

- $I_{BD}^i$  is the indicator for potential biological diversity degradation caused by the release of  $R^i$ . When it is one (1), it implies that there is a local problem related to biological diversity degradation caused by a specific release  $i$ .
- $V_{BD}^i$  is the control volume of the released waste  $R^i$  where the biological diversity degradation is expected to affect.
- $C_{BD}^i$  is the concentration of the released waste  $R^i$  at which the biological diversity degradation is expected to be effectuated.

In other words, the indicators are zero as long as the resulting increased concentration of a substance resulting from a release ( $R^i$ ) into the control volume is smaller than the concentration level for which biological degradation is expected to appear. It works similarly for human health (HH) risks, see Equation 7. These indicators should be used, but independently, with the WI when information is available. We feel that these indicators should not be used to affect the numerical magnitude of the WI because it reduces consistency and ultimately comparability.

## 6 Closure

Incomparability is one of the most severe problems of conventional LCA methods currently promoted for use in industry. To reduce this 'methods deficiency', as (AYRES, 1995) calls it, we believe that LCA methods must be revisited, with

a primary focus on eliminating the use of functional units, unit processes and impact categorization. As a step towards resolving these problems, we present the Waste Index (WI) which gives comparable results by eliminating the use of functional units, unit processes and environmental impact categorization by benchmarking Nature and using fundamental thermodynamics and chemistry principles. The Waste Index is an index that goes beyond merely assessing quantities of wastes (like done in inventories and mass balances), but stops short of a detailed assessment of the actual environmental impacts (e.g., specific effects to acidification, etc.) that are currently attempted in the conventional LCA methodology. We feel that the Waste Index provides an interesting and useful middle ground (or bridge) for those who wish more specificity in impact assessment than merely looking at quantities, but on the other hand, are weary about making actual impact assessments due to all the incomparability problems.

Another issue is that, according to (BERGMAN, 1994; TIBOR and FELDMAN, 1996), ISO 14000 is the 'environmental management system equivalent' of the ISO 9000 quality management standard and it is therefore constructed in a very similar manner. The highly acclaimed ISO 9000 standard has, however, *not* produced any measurable improvements in companies where it has been implemented, according to a survey by Certified Accountants in the U.K., see (BOWIE and OWEN, 1996). In fact, the ISO 9000 seems to be more a 'trade requirement' (MILES and RUSSEL, 1997), than a new powerful philosophy for the company. We have to learn from the ISO 9000 experience and be careful not make the same mistakes with ISO 14000.

We believe that we should stop standardizing things when we are standardizing the wrong things. We would propose to have ISO or similar organization work out Waste Index parameter publications and determine the conventions regarding waste material degradation (function, time, etc.), which base year to use, and (possibly) what standardized atmosphere – ocean – fresh water and – soil control volumes to use. Since the WI is comparable, that could form the basis for *waste accounting* – identical to monetary accounting, which is also something ISO could engage in and in fact create an ISO 14000 Waste Accounting Standard. Then, one could use the same cost management systems used today to also handle waste management by almost just adding an extra column, so to speak, to the cost management spreadsheets.

In any case, we certainly think it is time to think *differently*, and an initial step is taken here. We have no doubt that the WI can probably be formulated better and that more research is needed. However, it *does* have one indispensable feature, namely, comparability. This has been accomplished by benchmarking Nature and relying on fundamental principles in nature – the single most important message in this paper. Throughout the history of science 'truths' about Nature have been changing but the laws of Nature remain.

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